Progress Towards a Space-based Gravitational-Wave Observatory Since 2010

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Midterm Assessment Committee

Washington, DC, 9 October 2015

Outline

- State of Play in August 2010
- 2010-2015
  - The LISA Project and Subsequent Studies
  - LISA Pathfinder
  - Technology Development
  - ESA's Cosmic Visions Programme
  - Gravitational Wave Science
- The Plan Forward: 2016-2020

STATE OF PLAY IN AUGUST 2010

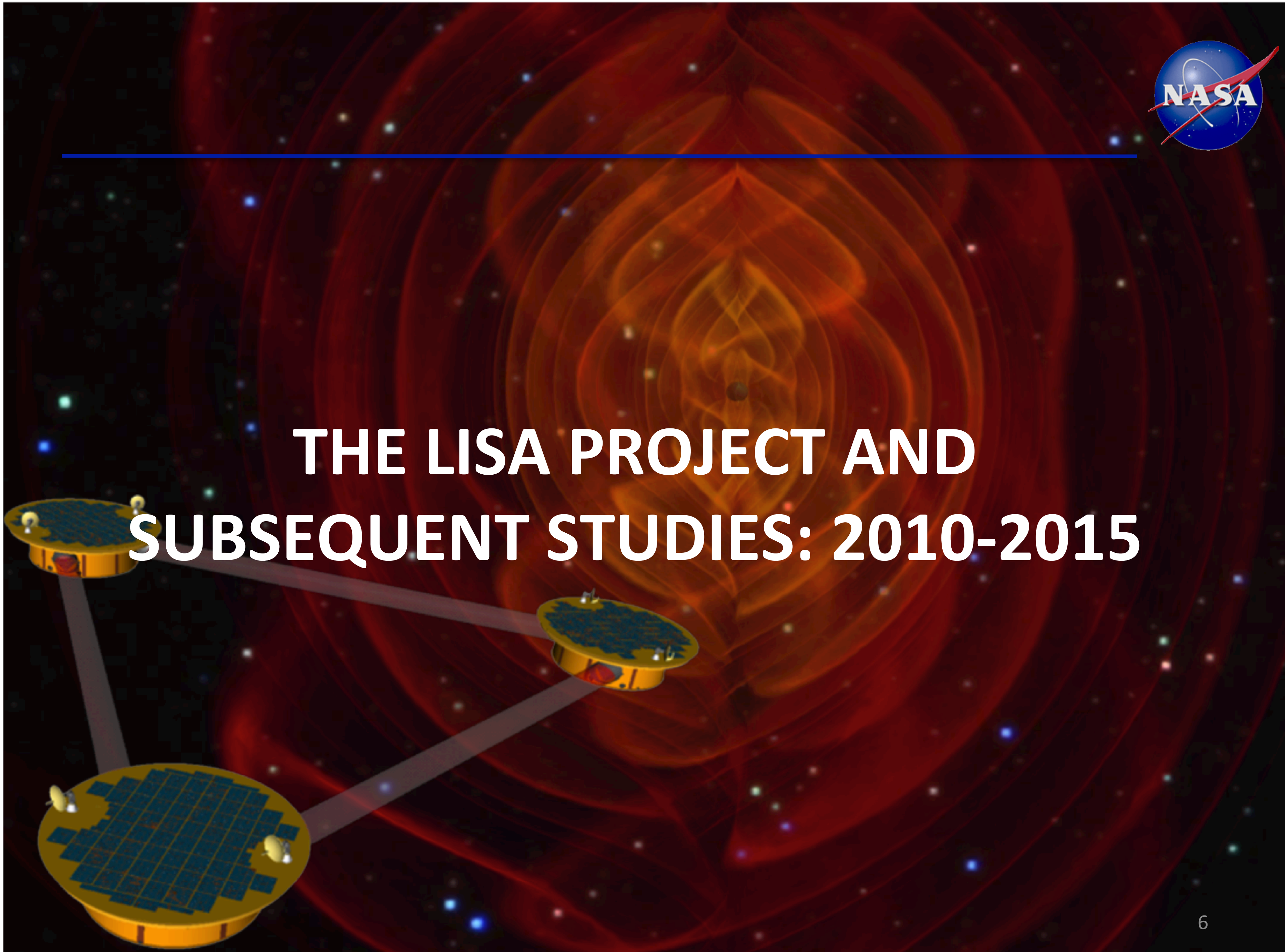
LISA in August 2010

Laser Interferometer Space Antenna (LISA)

- Focus of all work since 1993
- Unchanged since 1997
- Project in Phase A since 2004
- Extensive formulation work and products
- Reviewed and recommended in many major reviews:
  - AANM (NRC, 2001)
  - TRIP (HQ, 2003)
  - Connecting Cosmos to Quarks (NRC, 2003)
  - AETD (GSFC, 2005)
  - Beyond Einstein Program (NRC, 2007)
  - NWNH (NRC, 2010)
    - Second in 'large' space projects after WFIRST.
    - Recommended for a new start
    - Contingent on Pathfinder success and a roughly 50/50 European partnership.

ST7 in August 2010

- 2001: New Millennium Program selected the “Disturbance Reduction System” as Space Technology 7 (ST7)
- U.S. contribution to ESA’s LISA Pathfinder mission
- Original idea: NASA and ESA payloads, each with
  - 2 Gravitational Reference Sensors (GRSes)
  - Metrology interferometer
  - Microthrusters
  - Drag-free controller
- 2005: Descoped interferometer and GRSes
- 2010: Remaining U.S. hardware nearing completion.



THE LISA PROJECT AND SUBSEQUENT STUDIES: 2010-2015

The LISA Project

- March 2011: NASA withdrew from ESA's L1 proposals because of increased program demands and decreased budget projections.
- April 2011: Joint NASA/ESA LISA Project ended
- Science team disbanded
  - Working groups stopped working.
  - Mock LISA Data Challenge stopped.
- Project team at GSFC and JPL largely disbanded.
- Technology support transitioned to SAT grants

Probe Mission Concept Study

2011-2012: Study of probe class concepts ($\lesssim$\$1B)

- Design trade-offs explored for impact on science, risk and cost.
- No viable concepts near or below $1B
- No technology dramatically reduces cost
- LISA architecture can be scaled down (SGO Mid), still compelling science.
- Science performance decreases far more rapidly than cost. Risk increases to an unacceptable level.

Final report and (many) other documents at http://pcos.gsfc.nasa.gov/studies/gravitational-wave-mission.php

Technology Development Roadmap

2012-2013: prepared 'technology roadmap' for a future GW mission

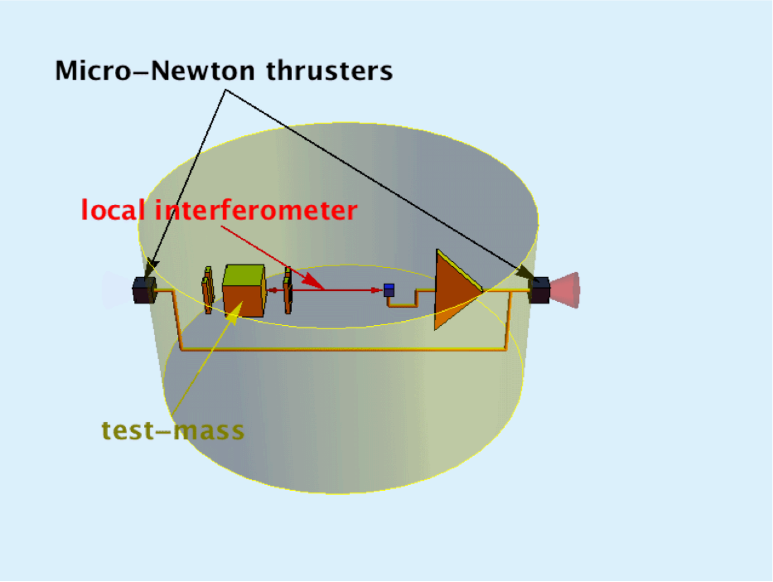
- The eLISA and SGO Mid concepts require the same technology.
- U.S.-centric plan to develop technologies for a LISA-like mission in the 2030's.
- *Predates* the selection of L3.
- Links to final document and annual program technology reports at http://pcos.gsfc.nasa.gov/technology/

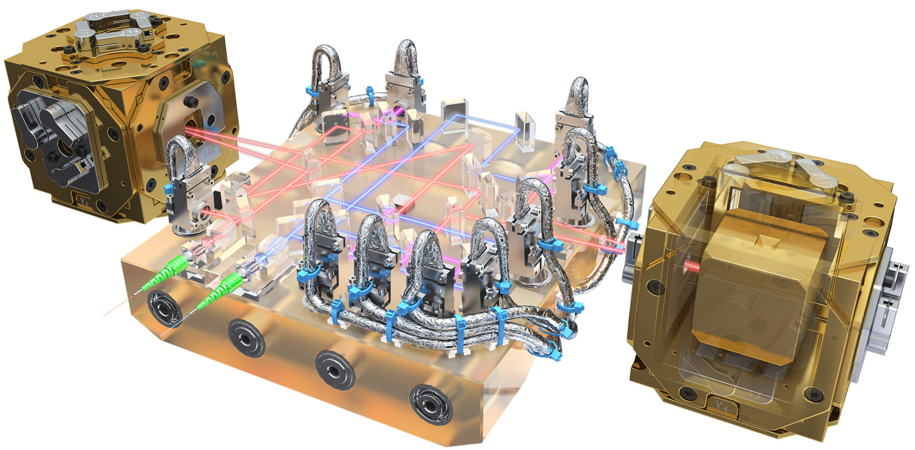
LISA PATHFINDER

LPF Objectives

- Drag-free flight demonstration
  - Residual acceleration on the test mass $<3\times10^{-14}$ m/sec^2/√Hz at 1 mHz
  - Multi-degree-of-freedom control system
- Microthruster demonstration
  - Thrust noise
  - Controllability
- Error budget validation
  - Programmable environment disturbances (magnetic, thermal, charging)
  - Measure the transfer function
  - Extrapolate to LISA

LPF – The Basic Idea

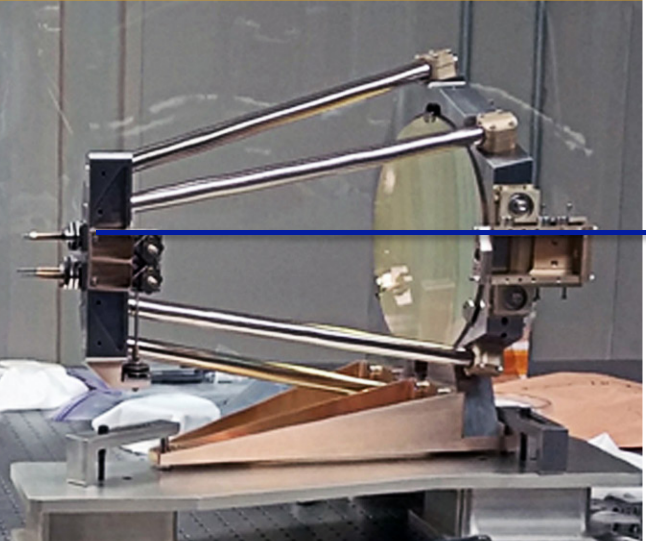


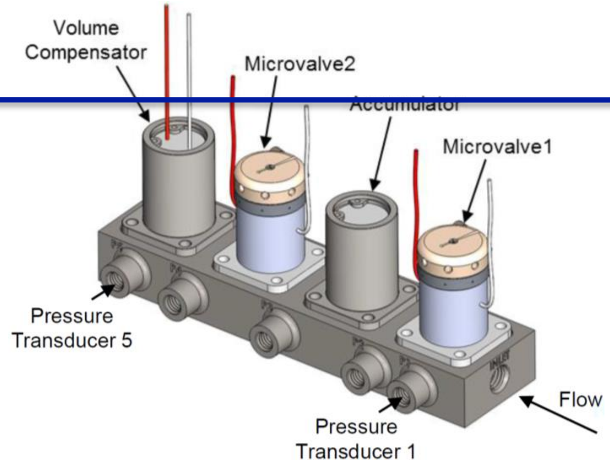


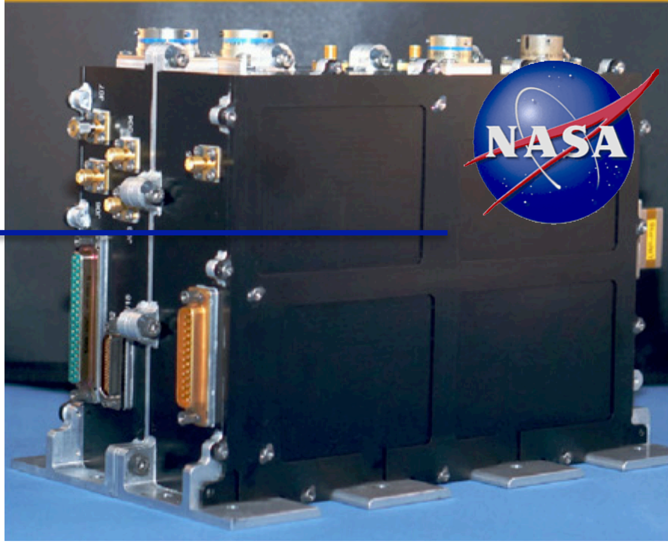
- Drag-free control system
  - One test mass as a sensor
  - Microthruster as a forcer.
  - Controller
- Second test mass as a "witness."
- Measure the relative motions of the two test masses with picometer interferometer

LPF – Status

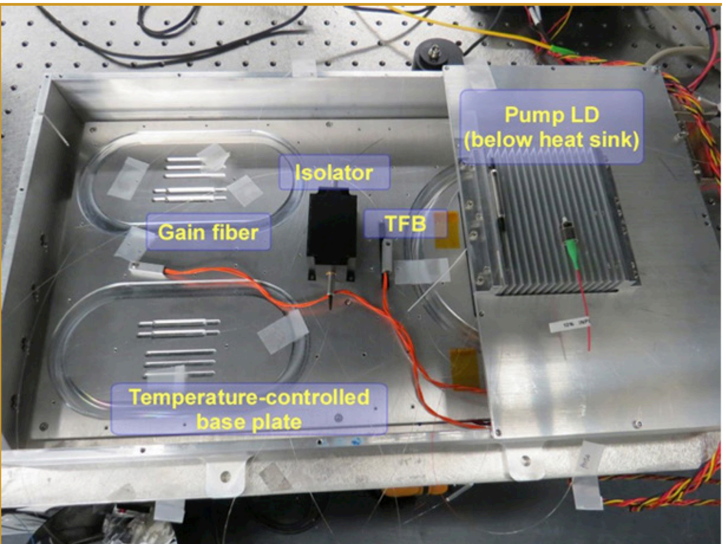
- 2012: ST7 delivered to ESA, integrated later in the year
- ESA thrusters changed to GAIA cold gas thrusters
- Final ground testing met or exceeded all requirements.
- September 3: spacecraft, propulsion module and launch I&T complete, ready for shipping
- Numerous operations exercises have been carried out.
- October 8: Flown to Kourou.
- December 1, 11:15 pm EST: scheduled launch on Vega 6
- L+74 d: LTP operations start
- L+186 d: ST7 operations start
- L+288 d: Nominal mission ends.
- Extended mission under consideration.

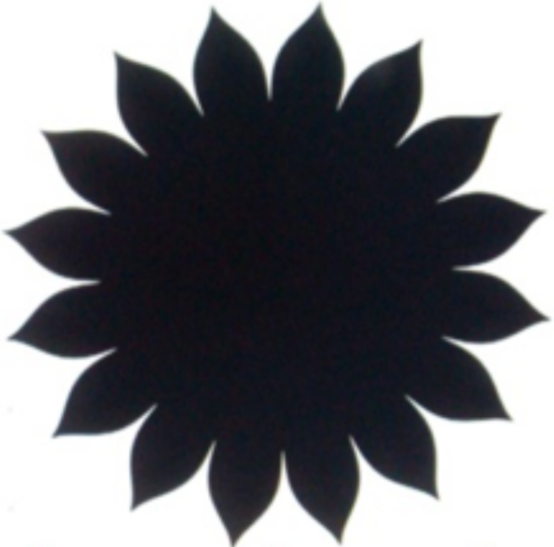


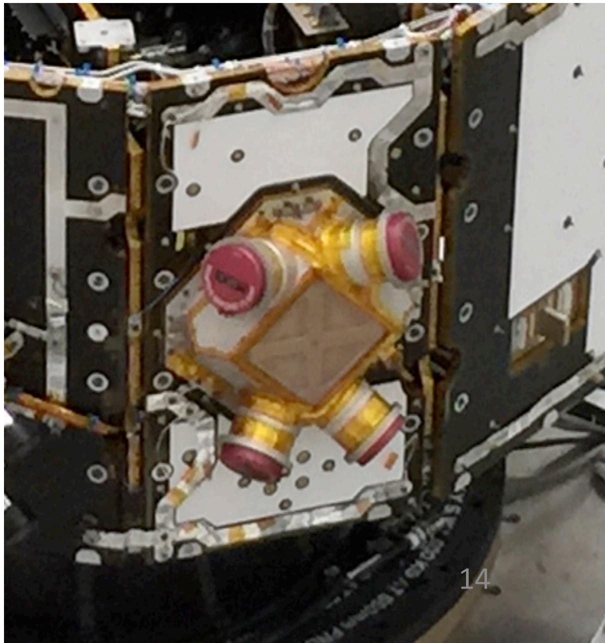




TECHNOLOGY DEVELOPMENT







Technology Development

- Telescope Subsystem – Jeff Livas (GSFC)
  - Demonstrate pathlength stability, stray light and manufacturability
  - SAT renewed FY16
- Phase Measurement System – Bill Klipstein (JPL)
  - Key measurement functions demonstrated
  - Incorporate full flight functionality
  - SAT expired
- Laser Subsystem – Jordan Camp (GSFC)
  - 1064 nm ECL master oscillator
  - Phase noise of fiber power amplifier
  - Demonstrate end-to-end performance in integrated system
  - Lifetime
  - SAT expires May ‘16
- Micronewton Thrusters – John Ziemer (JPL)
  - Propellant storage and distribution for long duration
  - Improve system robustness
  - Improve manufacturing yield
  - Lifetime
  - SAT expired

Technology Development

- Arm-locking Demonstration – Kirk McKenzie (JPL)
  - Studying a demonstration of laser frequency stabilization with GRACE Follow-On
  - Expiring APRA
- Torsion Pendulum – John Conklin (UF)
  - Develop U.S. capability with GRS and torsion pendulum test bed
  - Nancy Grace Roman Fellowship FY15-16
- Multi-axis Heterodyne Interferometry – Ira Thorpe (GSFC)
  - Investigate test mass/optical bench interface
  - APRA starting FY16
- UV LEDs – John Conklin+ (UF)
  - Flight qualify UV LEDs to replace mercury lamps in discharging system
  - Non-NASA support
- Optical Bench – Guido Mueller (UF)
  - Investigate alternate designs and fabrication processes to ease manufacturability
  - APRA starting FY16

LISA researchers at JPL are leading the Laser Ranging Interferometer instrument on the GRACE Follow-On mission.

ESA’S COSMIC VISION PROGRAMME 2015-2025

Cosmic Visions 2015-2025

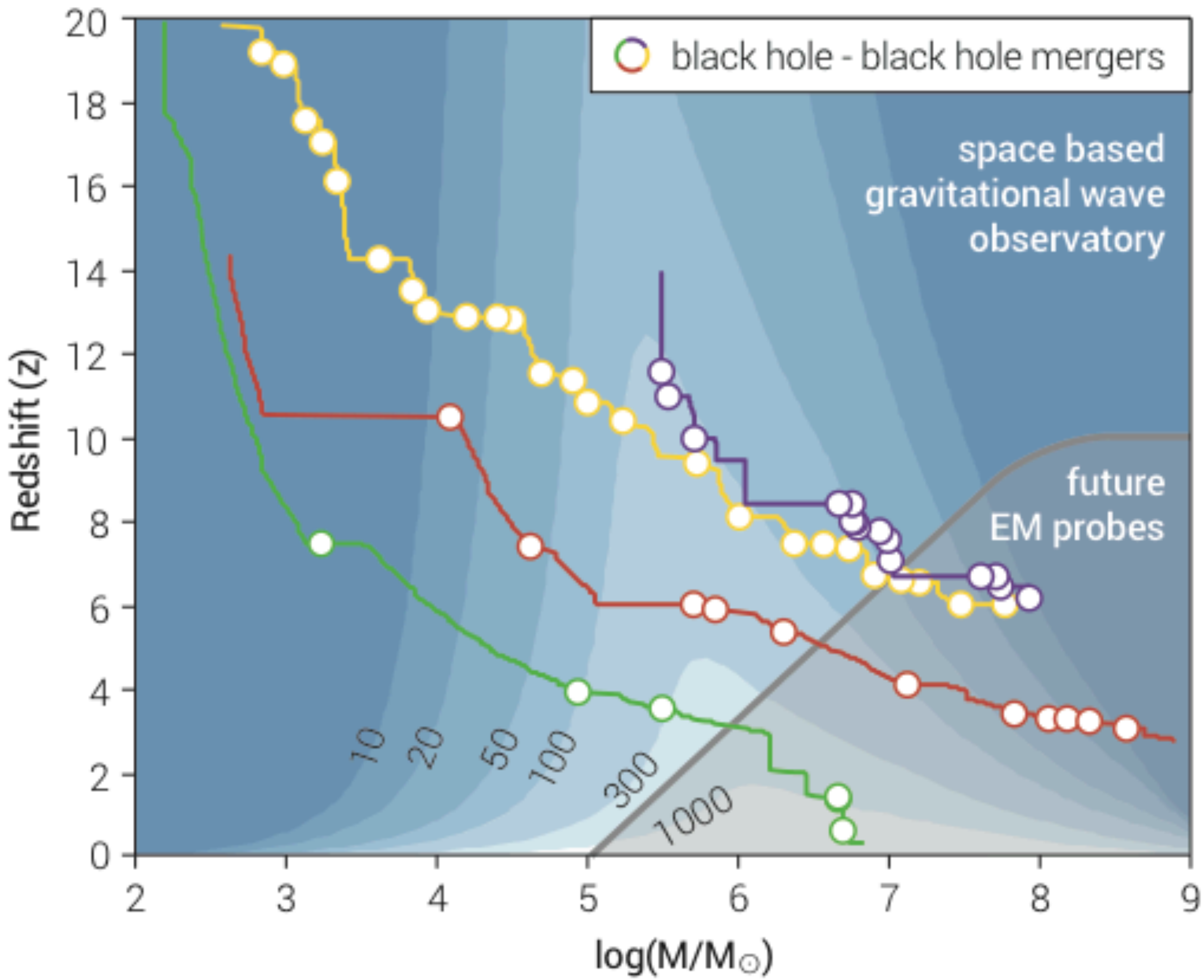
- Next “planning horizon” for ESA science
- NASA withdrew from initial L1 competition in 2011.
- Next Gravitational Observatory (NGO) concept proposed to second L1 competition in 2012.
  - Descoped LISA-like mission to meet ESA cost cap without US participation
  - *Two arms, 1 million Km baselines, 2 year science operations,* 2 launches, mother-daughter configuration.
  - JUICE selected
- “Gravitational Universe” proposed for L2/L3 Competition in 2013
  - NGO the “notional” mission concept.
  - Senior Selection Committee selected Athena for L2 and the Gravitational Universe as the “science theme” for L3, on account that LPF had not yet flown.

ESA’s L3 Mission

- Only ‘science theme’ selected, not a mission concept
- Planned launch date is 2034.
- Cost cap is 1B€ to ESA.
- Member states typically contribute an additional 30-35%.
- International partners limited to 20% of total European contribution (about $300M).
- NASA interested at the $100-150M level
- ESA included three U.S. members and one NASA observer on the Gravitational Observatory Advisory Team (GOAT)

GRAVITATIONAL WAVE SCIENCE

LISA and Cosmological Structure Formation



Advances in LISA Science

- Improvements in MBHB parameter estimation
  - Added merger and ring-down phases to waveforms
  - Added higher harmonics to waveforms
  - Improved understanding of sky localization, especially from merger phase
  - Orbital eccentricity explored
  - Improved understanding of the interaction between SMBHs and their host galaxies, including effects of eccentricity and spin alignments
  - Kicks explored
  - Improved cosmological modeling of structure formation
  - Better understanding of final parsec problem and its resolution
- Emerging methods for quantifying GR tests
- Science performance calculations
  - ~50 mission concept variants analyzed

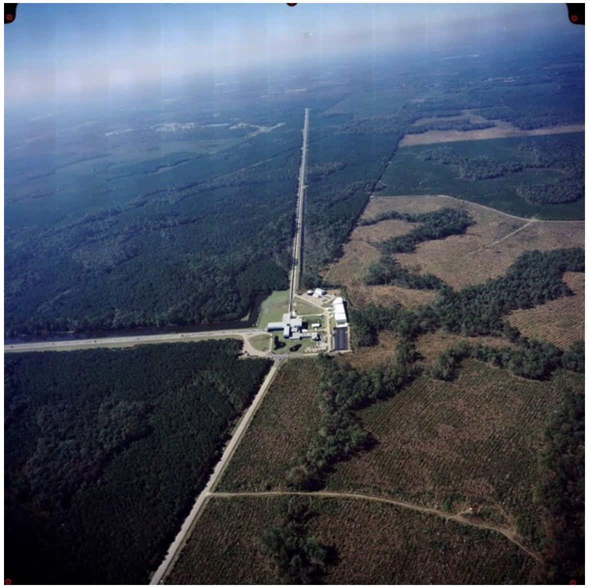
2010s – The GW Decade

Advanced LIGO/Virgo/KAGRA begin operations

- O1 observing run began September 18th for 3 months
- Reach 70 Mpc for NS-NS mergers, 3 times previous LIGO distance (27 times volume)
- Progressive sensitivity improvement in next few years
- First GW observations expected by ~2019

Pulsar Timing Arrays (PTAs)

- Several PTA efforts have published upper-limits on stochastic GW backgrounds from SMBH binary mergers (NANOGrav, EPTA, PPTA)
- A key astrophysical uncertainty is in the strength of SMBH binary interactions with their environments
- Recent (2015) results from Parkes (PPTA) are in conflict with models that assume modest rates of evolution passing through the nHz band.
- Models less sensitive to environmental effects at higher frequencies



Caltech/MIT/LIGO Lab

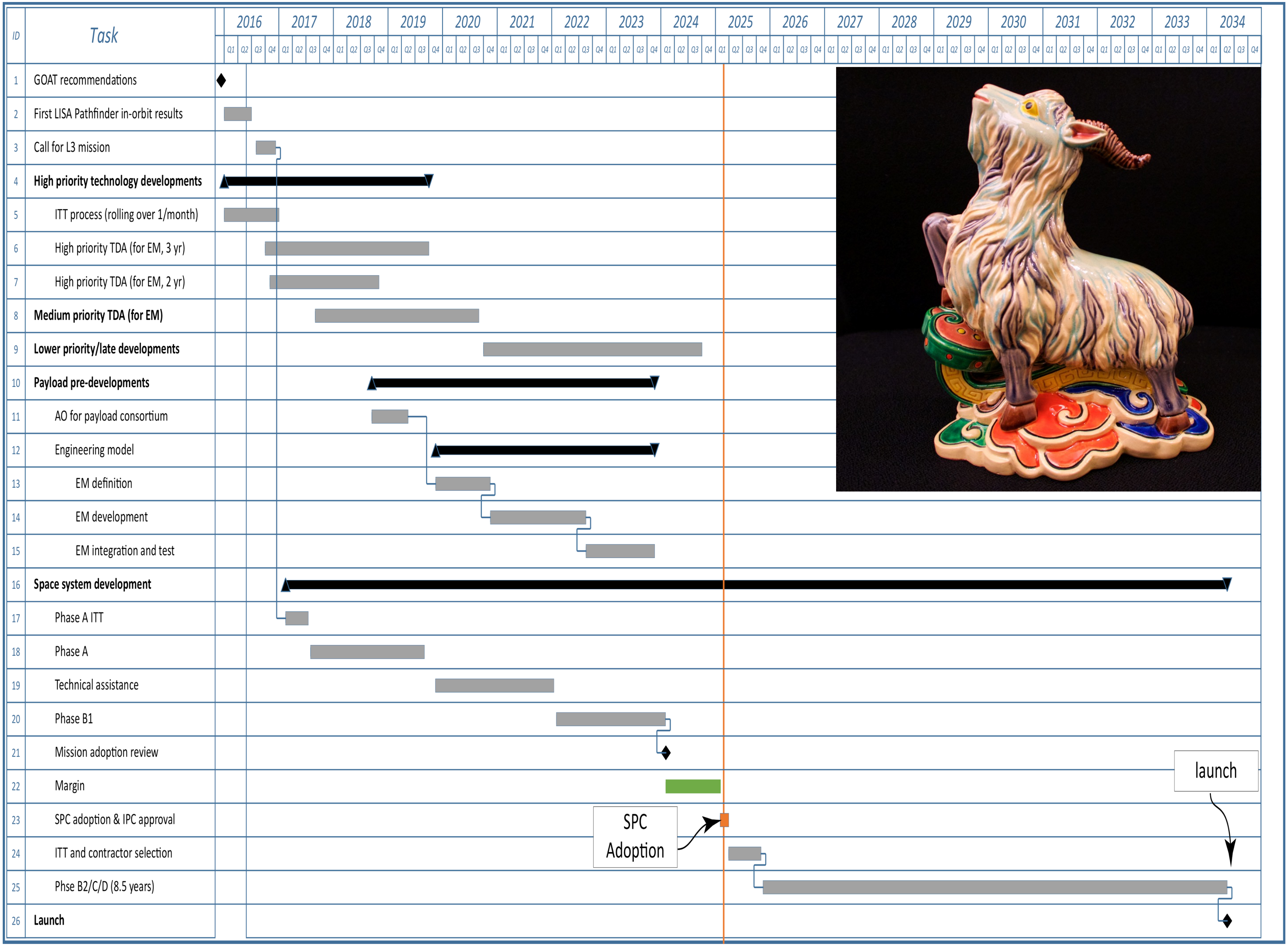
Caption: CSIRO's Parkes radio telescope. Credit: David McClenaghan, CSIRO

THE PATH FORWARD: 2016-2020

Gravitational Observatory Advisory Team (GOAT)

- GOAT: an ad-hoc ESA advisory committee initiated in September 2014:

  "To evaluate and recommend on possible scientific and technical approaches for a gravitational wave observatory envisaged for a planned launch date in 2034."
- 3 US members and 1 NASA observer out of 12 total, very active in the internal studies and debates
- Topics: technical feasibility, science goals, data analysis, system view, technology, partners, cost and schedule
- GOAT has been asked to assess LPF success, with addition of European and US experts. (cf. NWNH)
- GOAT Intermediate Report and other material at: http://www.cosmos.esa.int/web/goat/home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Q1 Q2 Q3 Q4
1 GOAT recommendations
2 First LISA Pathfinder in-orbit results
3 Call for L3 mission
4 High priority technology developments
5 ITT process (rolling over 1/month)
6 High priority TDA (for EM, 3 yr)
7 High priority TDA (for EM, 2 yr)
8 Medium priority TDA (for EM)
9 Lower priority/late developments
10 Payload pre-developments
11 AO for payload consortium
12 Engineering model
13 EM definition
14 EM development
15 EM integration and test
16 Space system development
17 Phase A ITT
18 Phase A
19 Technical assistance
20 Phase B1
21 Mission adoption review
22 Margin
23 SPC adoption & IPC approval
24 ITT and contractor selection
25 Phse B2/C/D (8.5 years)
26 Launch
SPC Adoption
launch

Pre-decadal Study

- NASA participation in L3 needs a strong recommendation from Astro2020 to go forward.
- NASA needs to define its role, <u>and</u> understand the options
    - Starting point: $100-150M contribution
    - ESA's limit: 20% of European contribution (~$300M)
    - Contributions: elements of the flight system
    - U.S. activities: science team, data analysis, data center, guest observer program
    - Cost and schedule estimates for collaboration, technology development, flight system contributions and U.S. activities
- Produce the basis for a proposal to Astro2020 by late 2018.

NASA activities 2015-2017

- Operations and data analysis on Pathfinder and ST7
- GW Science Interest Group/Physics of the Cosmos Program Analysis Group (POCs: John Conklin and Neil Cornish)
- Continued participation in ESA's GOAT
- Participation in early ESA lead-in activities: mission concept proposal/selection, ESA's Phase A starts 2017, …
- Technology development to meet the L3 schedule (ISO TRL6 by Q4 2019)
- Rebuild a supporting GW community in the US
- Pre-decadal study in 2017-2018
- Preparations for next decadal

NASA activities 2018-2020

- GW Science Interest Group/Physics of the Cosmos Program Analysis Group
- Participation in early ESA lead-in activities: payload AO, payload engineering model, …
- Technology development to meet the L3 schedule (ISO TRL6 by Q4 2019)
- Pre-decadal study in 2017-2018
- Continue rebuilding US research community
- Astro2020 decadal survey, a US role in L3 needs
  - A strong endorsement for science and feasibility.
  - Recommended financial commitment

Wrap-Up

- NASA's strategic plan for a gravitational wave observatory is to participate in ESA's L3 mission
- To carry out that plan, NASA has to
  - Participate in the successful execution of LPF and ST7, baseline and extended missions
  - Successfully negotiate a role with ESA
  - Refine its plan through a pre-decadal study
  - Develop appropriate technology and participate in pre-formulation studies on ESA's schedule
  - Receive an endorsement for L3 participation from the 2020 decadal review

BACKUP

Mission Concept Comparison

Parameter	NGO	SGO Mid	LISA
Measurement arm length	1 x 10^6 km	1 x 10^6 km	5 x 10^6 km
Number & type of spacecraft	1 corner (2 optical assemblies, 2 end (single optical assembly	3 corner (2 optical assemblies)	3 corner (2 optical assemblies)
Number of measurement arms, one-way links	2 arms, 4 links	3 arms, 6 links	3 arms, 6 links
Constellation	Vee	Triangle	Triangle
Gravitational-wave polarization measurement	Single instantaneous polarization, second polarization by orbital evolution	Two simultaneous polarizations continuously	Two simultaneous polarizations continuously
Orbit	Heliocentric, earth-trailing, drifting-away 9°- 21°	Heliocentric, earth-trailing, drifting-away 9°- 21°	22° heliocentric, earth-trailing
Trajectory	Launch to Geosynchronous Transfer Orbit, transfer to escape, 14 months	Direct injection to escape, 18 months	Direct injection to escape, 14 months
Duration of science observations	2 years	2 years	5 years
Launch vehicle	Two Soyuz-Fregat	Single Medium EELV (e.g., Falcon 9 Block 3)	Single Medium EELV (e.g., Atlas V 551)
Optical bench	Low-CTE material, hydroxy-catalysis construction	Low-CTE material, hydroxy-catalysis construction	Low-CTE material, hydroxy-catalysis construction
Laser	2 W, 1064 nm, frequency and power stabilized	1 W, 1064 nm, frequency and power stabilized	2 W, 1064 nm, frequency and power stabilized
Telescope	20 cm diameter, off-axis	25 cm diameter, on-axis	40 cm diameter, on-axis
Gravitational Reference Sensor	46 mm cube Au:Pt, electrostatically controlled, optical readout	46 mm cube Au:Pt, electrostatically controlled, optical readout	46 mm cube Au:Pt, electrostatically controlled, optical readout

Science Comparison

	NGO	SGO Mid	LISA
MBH Totals	40-47	41-52	108-220
Detected z > 10	1-3	1-4	3-57
Both mass errors < 1%	13-30	18-42	67-171
One spin error < 1%	3-10	11-27	49-130
Both spin errors < 1%	<1	<1	1-17
Distance error < 3%	3-5	12-22	81-108
Sky location < 1 deg^2	1-3	14-21	71-112
Sky location < 0.1 deg^2	<1	4-8	22-51
EMRIs	12	35	800
Resolved CWDBs	3,889	7,000	40,000
Interacting	50	100	1,300
Detached	5,000	8,000	40,000
Sky location < 1 deg^2	1,053	2,000	13,000
Sky location < 1 deg^2, distance error < 10%	533	800	8,000
Stochastic Background	0	0.2	1

Special acknowledgement to Ryan Lang (Univ. of Florida) and Neil Cornish (Montana State Univ.)

What LPF does/doesn't demonstrate

- **Free flying test mass subject to very low parasitic forces:**
  - Drag free control of spacecraft (non-contacting spacecraft)
  - Low noise micro-thruster to implement drag-free
  - Large gaps, heavy masses with caging mechanism
  - High stability electrical actuation on cross degrees of freedom
  - Non contacting discharging of test-masses
  - High thermo-mechanical stability of S/C
  - Gravitational field cancellation
- **Precision interferometric, local ranging of test-mass and spacecraft:**
  - pm resolution ranging, sub-mrad alignments
  - High stability monolithic optical assemblies
- **Precision 1 Mo km spacecraft to spacecraft precision ranging:**
  - High stability telescopes
  - High accuracy phase-meter
  - High accuracy frequency stabilization
  - Constellation acquisition
  - Precision attitude control of S/C